Planning for NDCX-II, a next-step platform for ion beam-driven Warm Dense Matter studies*

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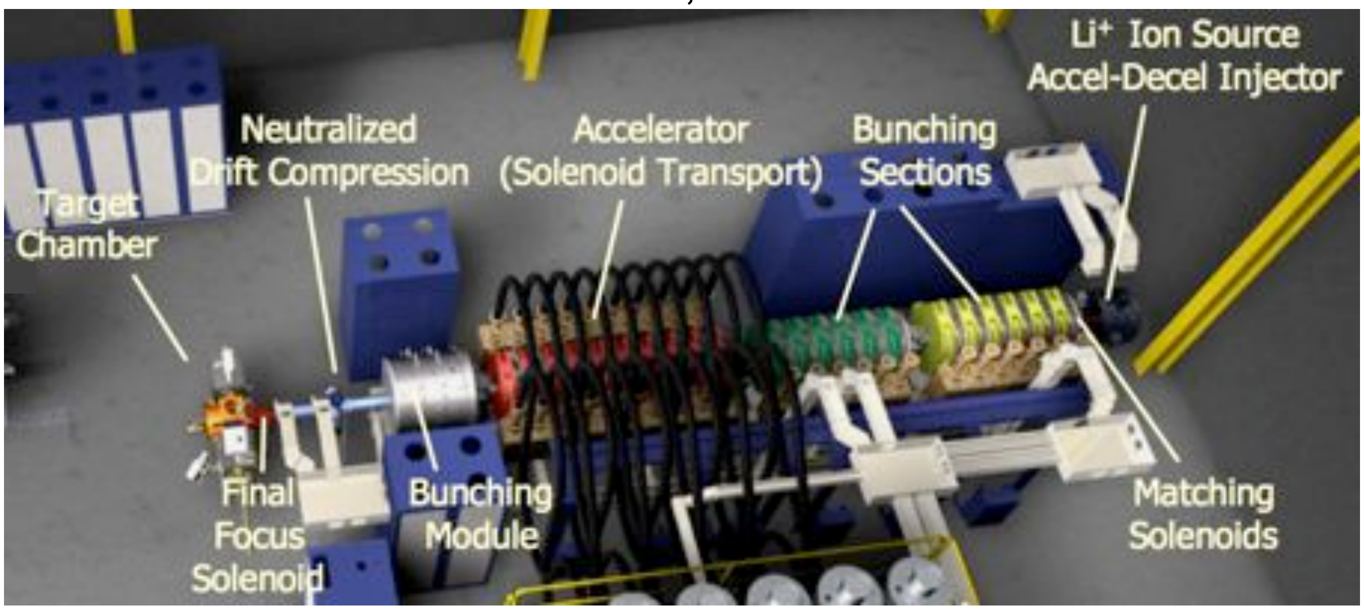


The HIFS-VNL has sufficient ATA parts to build NDCX-II, *enabling WDM experiments at the Bragg peak and studies of ion direct-drive physics*

The Heavy Ion Fusion Science Virtual National Laboratory

*This work was performed under the auspices of the U.S. Department of Energy by LLNL, in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344; by LBNL under Contract DE-AC02-05CH11231; and by PPPL under Contract DE-AC02-76CH03073.

DOE priorities include an ion-driven Warm Dense Matter facility

From *An Interim Report on Facilities for the Future of Science* (August 2007):

Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX)

Update: Mission Need for the IB-HEDPX (formerly called the Integrated Beam Experiment, or IBX), an intermediate-scale experiment using heavy ion beams for research on Warm Dense Matter (a midway state between solid matter and plasmas), was approved by the Department in 2005. Small-scale experiments are planned in 2008-2009 as part of R&D to provide a scientific basis for the new facility.

An IB-HEDPX capability for integrated acceleration compression and focusing on high current, space-charge-dominated beams would be unique—not available in any existing accelerator in the world.

- Experiments planned for 2008-2009 will use the existing NDCX-I
- NDCX-II, to be proposed, will satisfy an IB-HEDPX pre-requisite

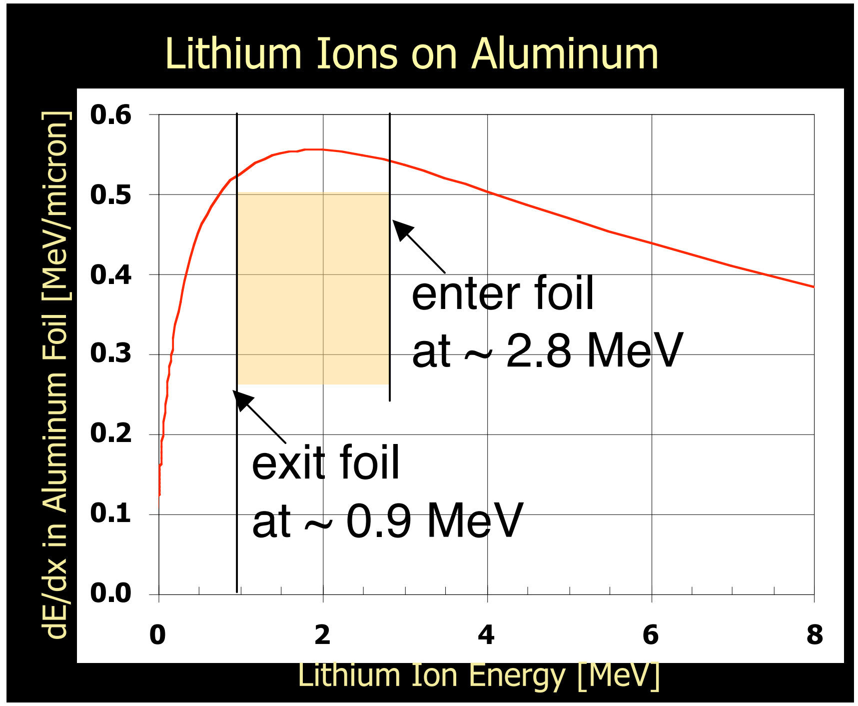
Bragg-peak deposition of heavy ion energy offers unifom, volumetric heating for Warm Dense Matter experiments

A LOW-RANGE ION APPROACH
Is being pursued by the U.S. HIFS-VNL

- low energy (~ few to 10's of MeV) allows smaller system
- uniform, efficient heating, as ions slow through Bragg peak
- If no hydro motion, 30 J/cm^2 yields ~ 2 eV

Requires:

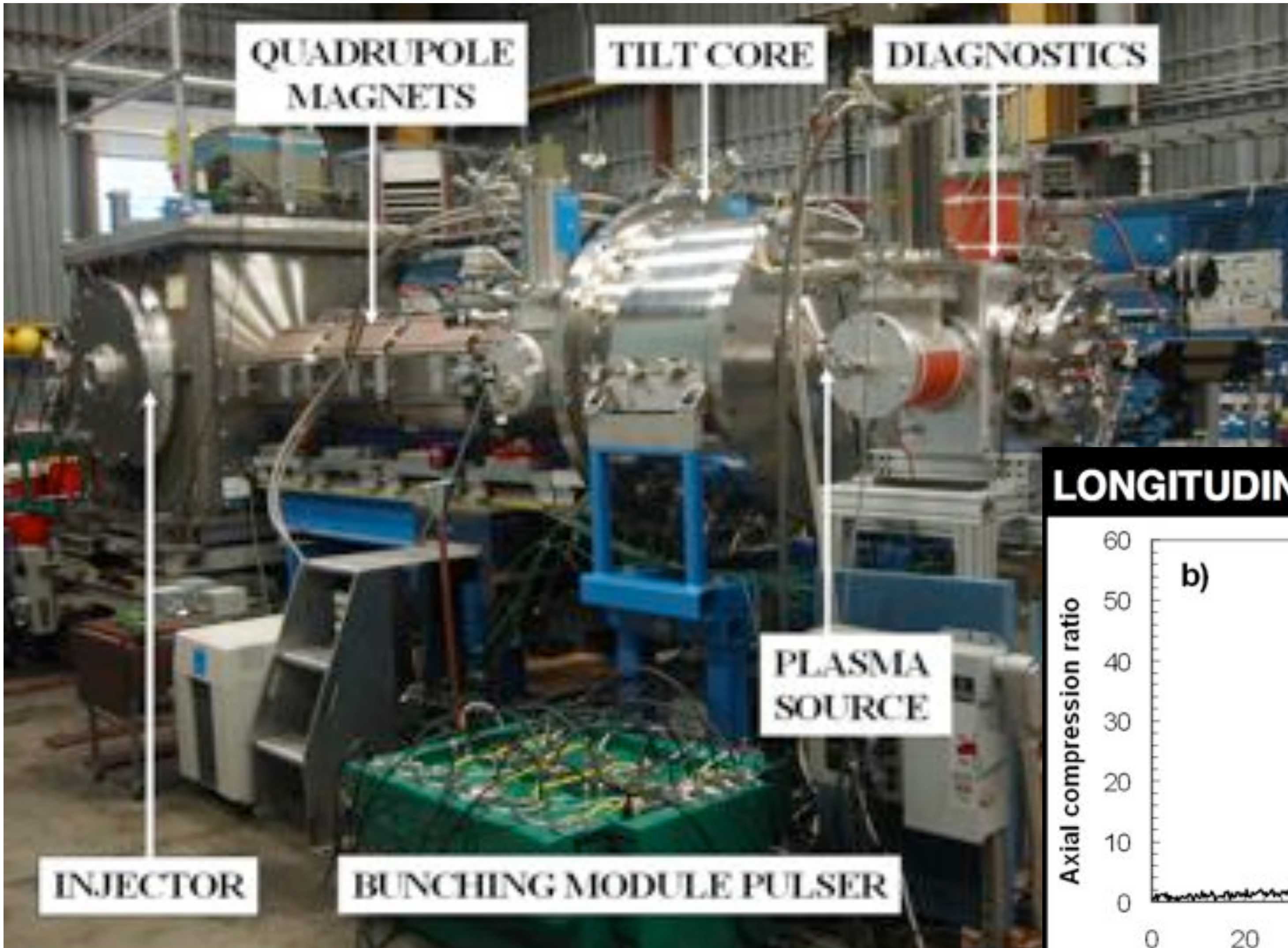
- **neutralized drift compression and focus** due to space charge
- **short pulses** to limit hydro motion (1 ns)
- **thin foil targets** (few μm) or foams

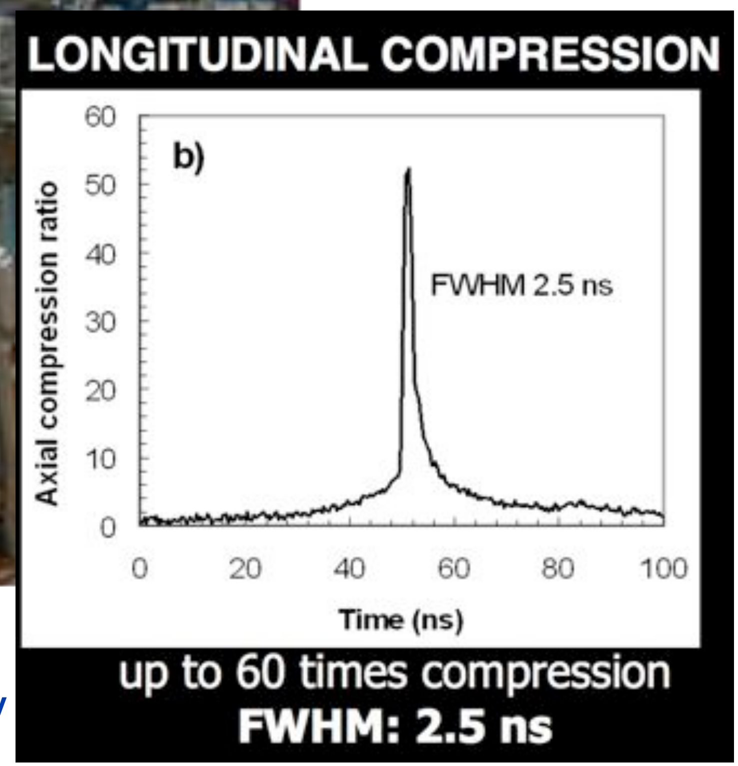


A complementary
HIGH-RANGE ION APPROACH
is being pursued by GSI in Darmstadt, Germany

- requires synchrotron, storage ring
- 40 to 100 GeV heavy ions, 50 - 100 ns
- large targets (several mm)

Neutralized drift compression experiment (NDCX-I) showed that plasma can cancel a beam's space-charge repulsion





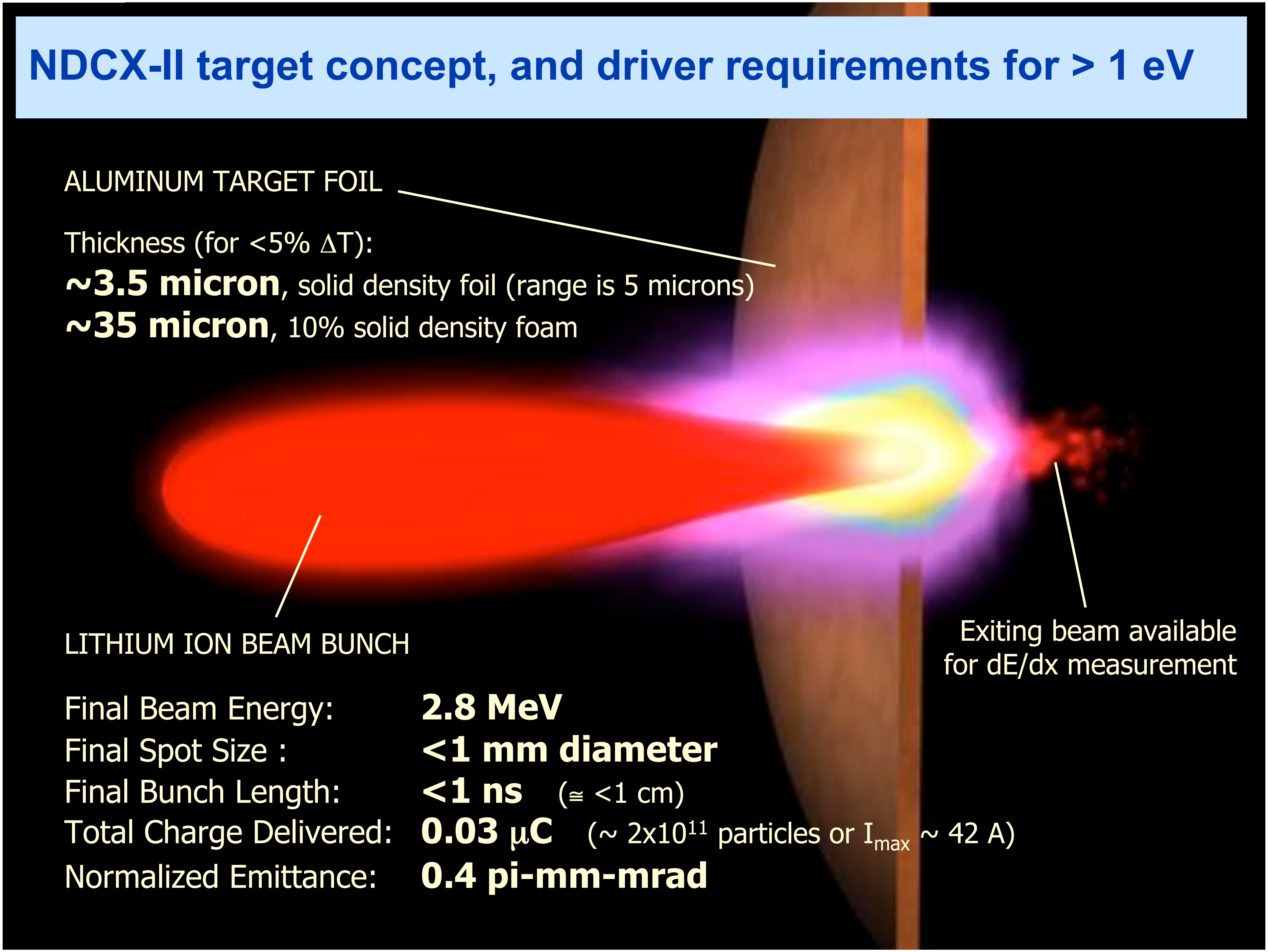
NDCX-I can do more still …

- **NDCX-1 will generate low-energy, space-charge neutralized, short-pulse ion beams, for the initial WDM target experiments in the US Heavy Ion Fusion Science Program (400 keV K^+ beam)**

- **We anticipate that beam compression in neutralizing plasma, in combination with an 8 Tesla final focus solenoid, can produce sub-mm spot sizes at ns pulse lengths (per simulations by A. Sefkow and D. R. Welch)**

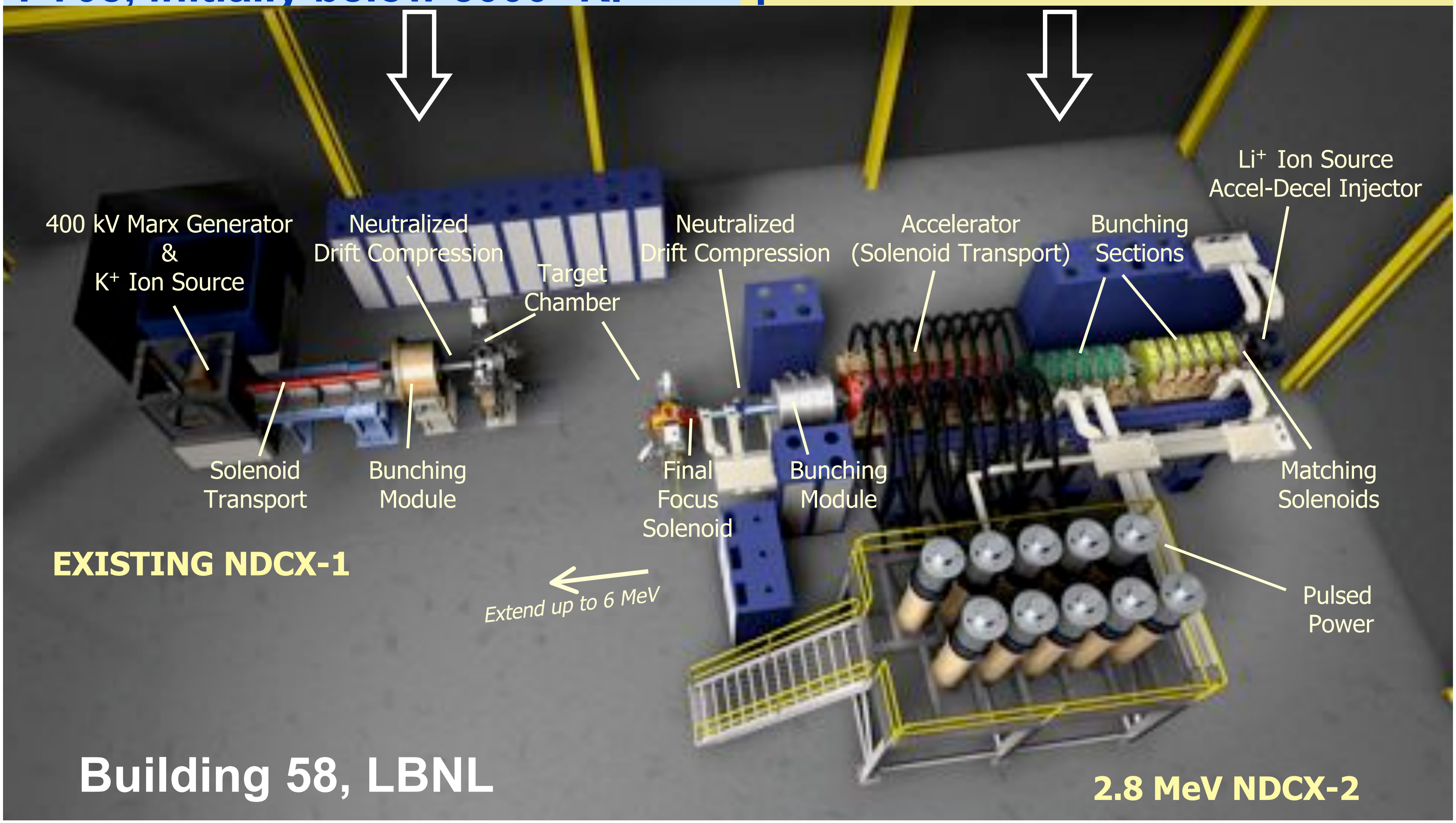
- ***BUT acceleration is still missing for 1 eV "Bragg peak heating"***

NDCX-II will accelerate beams to the requisite energies, and focus them onto small spots


NDCX-II target concept, and driver requirements for > 1 eV
ALUMINUM TARGET FOIL
Thickness (for <5% ΔT):
~3.5 micron, solid density foil (range is 5 microns)
~35 micron, 10% solid density foam
LITHIUM ION BEAM BUNCH
Exiting beam available for dE/dx measurement
Final Beam Energy: 2.8 MeV
Final Spot Size : <1 mm diameter
Final Bunch Length: <1 ns (≅ <1 cm)
Total Charge Delivered: 0.03 μC (~ 2x10^{11} particles or I_{max} ~ 42 A)
Normalized Emittance: 0.4 pi-mm-mrad

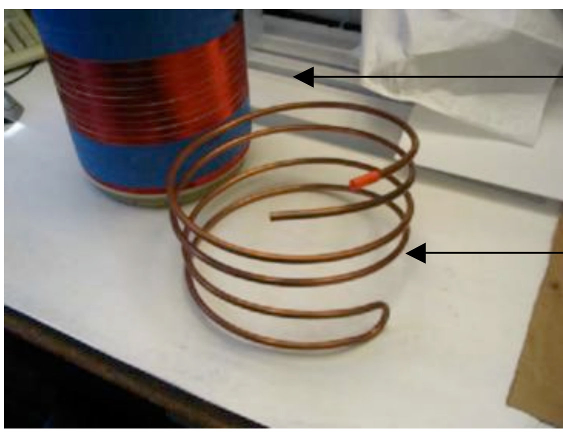
NDCX-I is being upgraded this year for first mm-scale warm dense matter experiments in FY08, initially below 5000º K.

NDCX-II, with 10X more beam energy using existing induction modules from ATA, is being planned for initial use in 2010



Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility

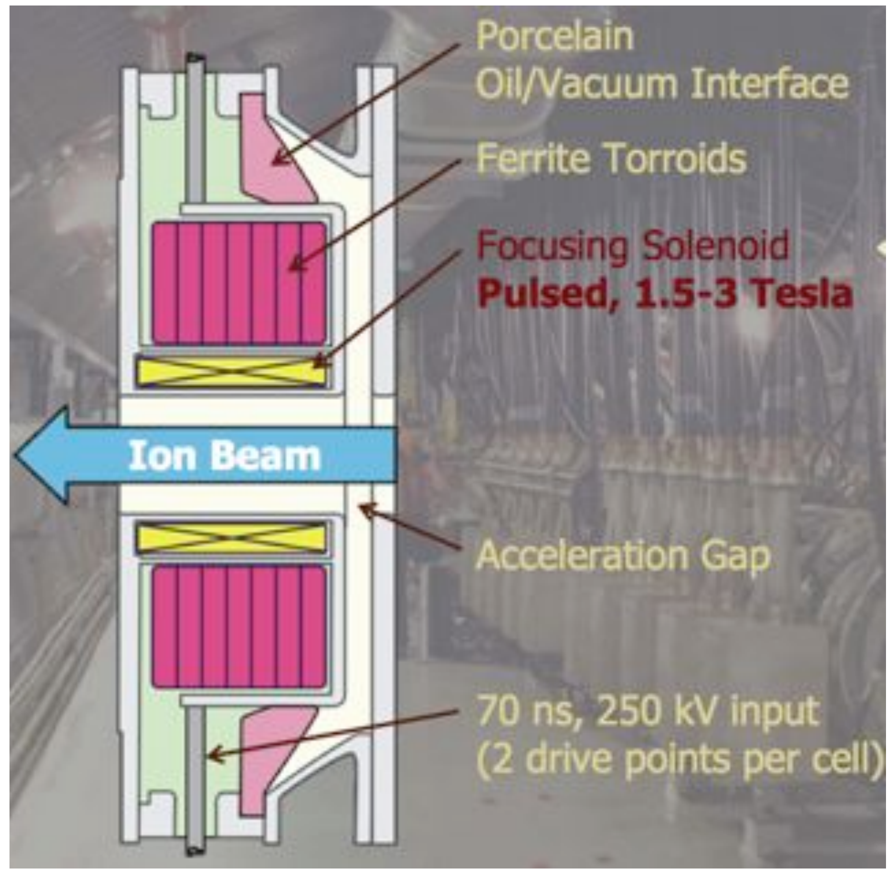
Test stand has begun to verify performance



solenoid

water cooling

Cells will be refurbished with stronger, pulsed solenoids

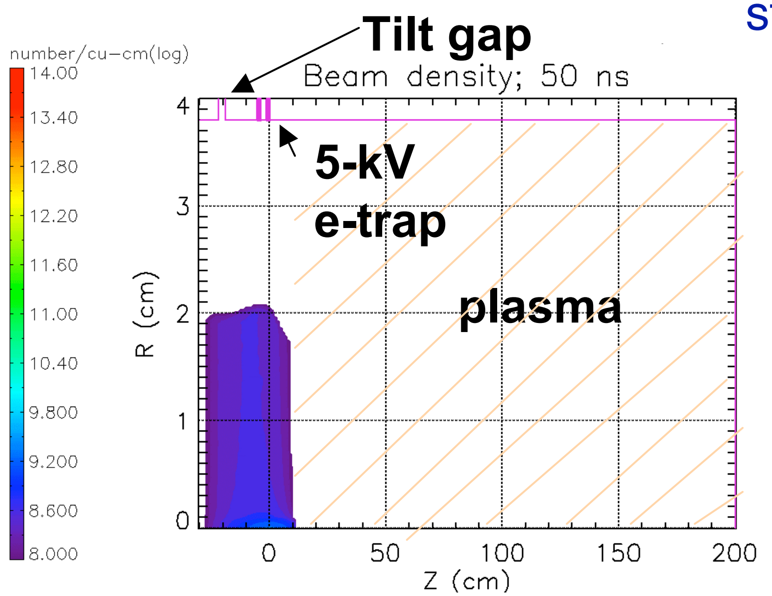


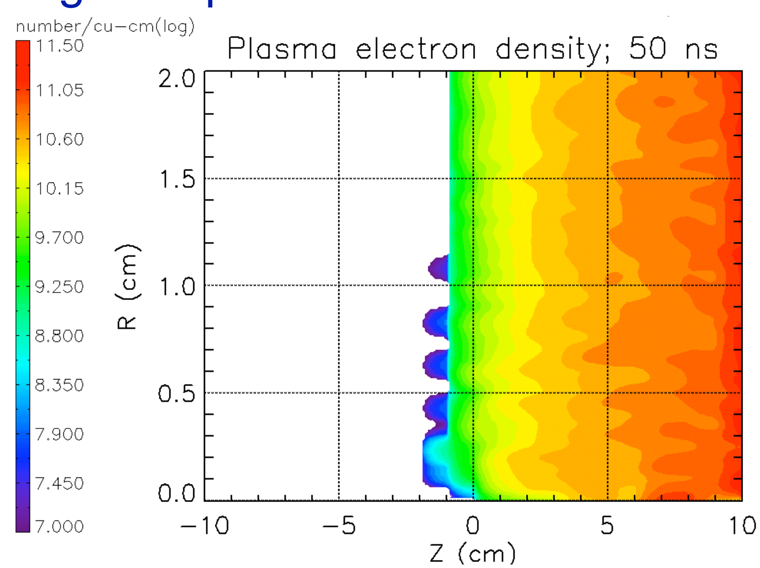
LSP is used to model neutralized compression and focus in NDCX-II (we plan to use both Warp & LSP in future)

- Idealized beam from accelerator, so far:
  - Li^+, 2.8 MeV with 1.67 eV temperature
  - 2-cm -5 or -6.7 mrad convergence; uniform current density; ε = 24 mm-mrad
  - 0.7-A current with parabolic 50-ns profile; applying ideal tilt for 30 ns of beam

- Uniform plasma: $n_p = 3 \times 10^{12}$, 3×10^{13} cm^{-3}, and an "optimistic" Ohm's law model

Short time scale plasma/vacuum interface is fairly stable; long-time plasma confinement is an issue

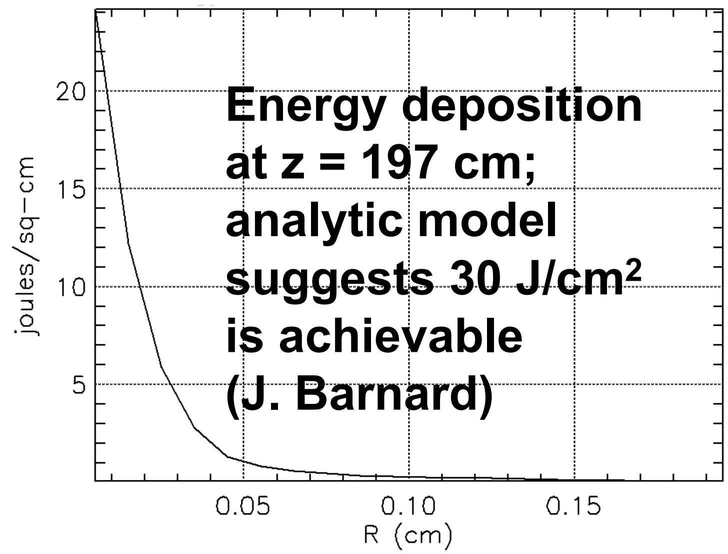


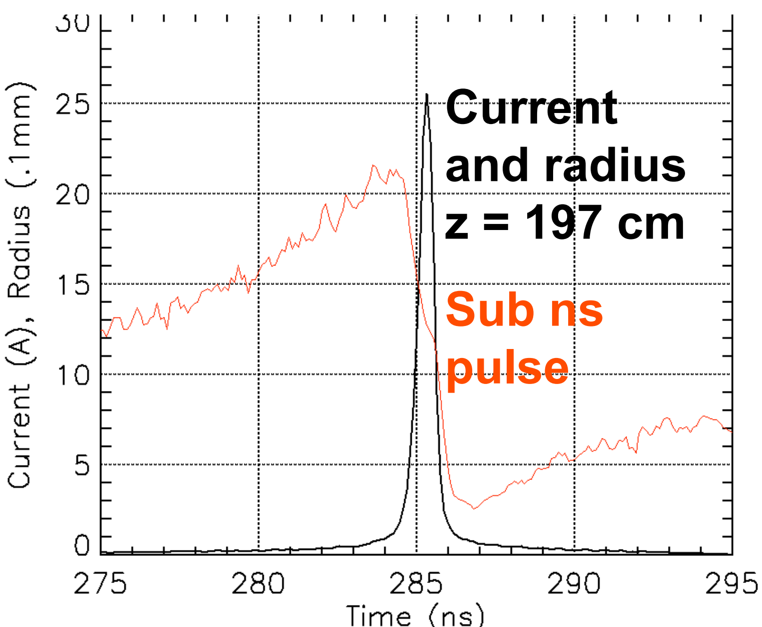


(these simulations by D. Welch; others by A. Sefkow)

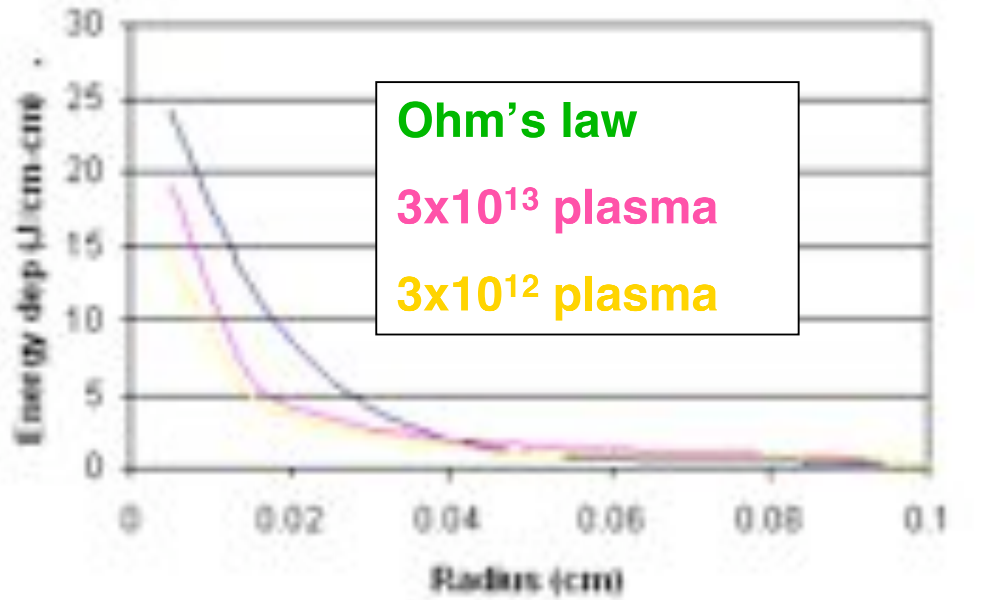
Results suggest plasma of density ~ 10^{14} cm^{-3} is desirable

Ohm's law result





Kinetic plasma result is somewhat degraded

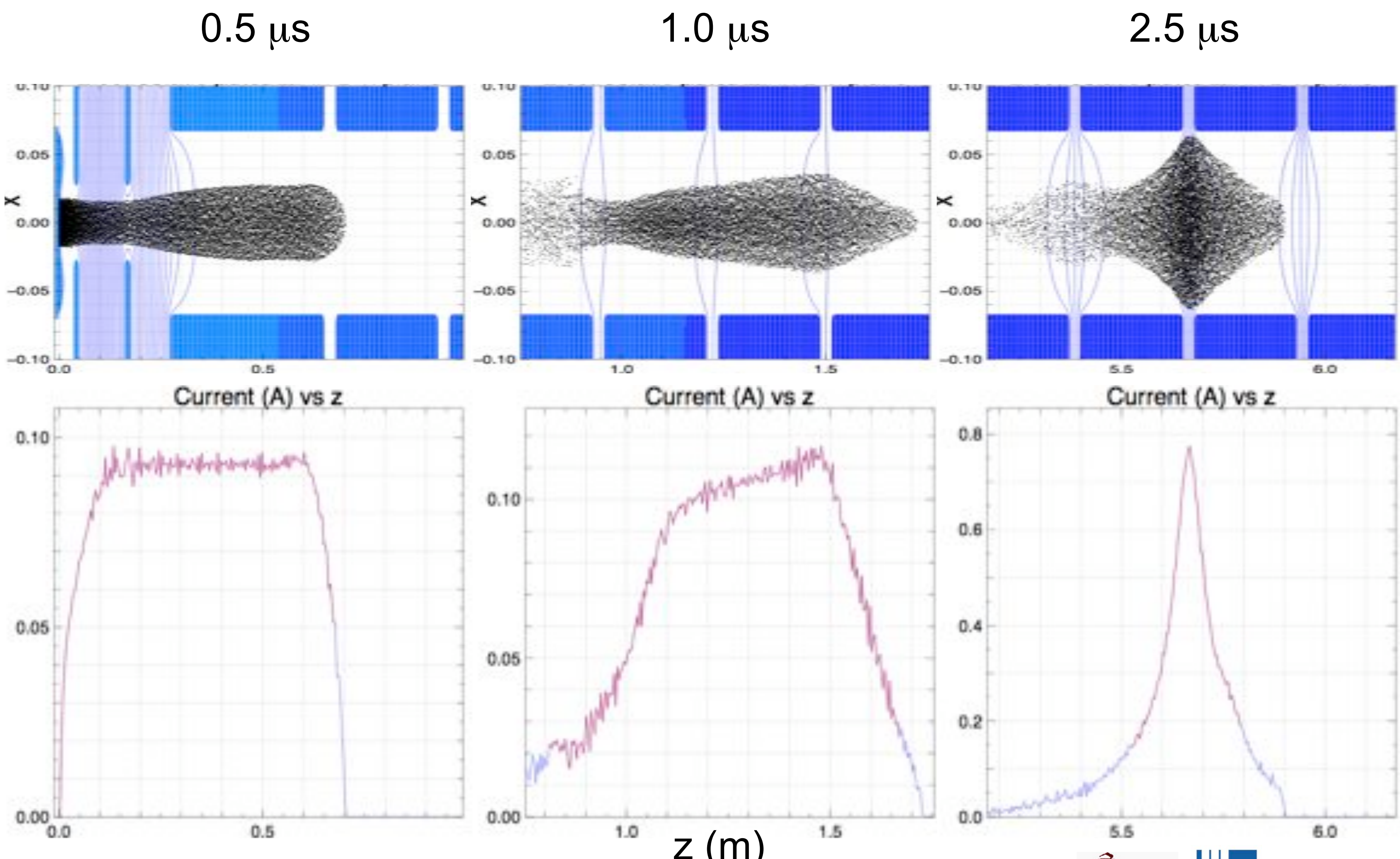


(½ mm 1-ns beam has 2×10^{13} cm^{-3} density)

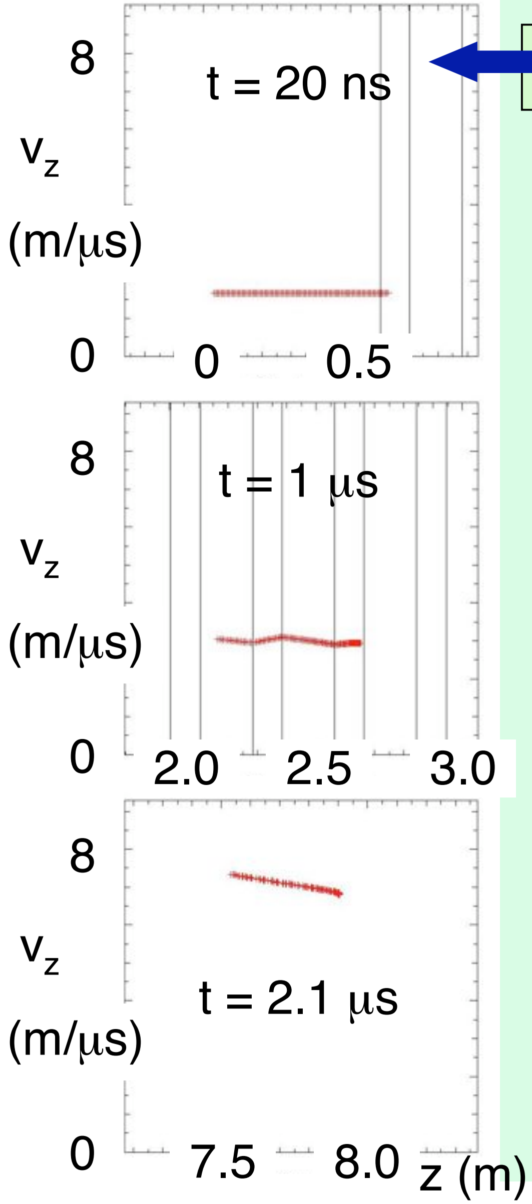
Still to do:

- Initialize beam using Warp output
- Correct chromatic variation via time-dependent focus
- Transport beam through "self-consistent" plasma

Self-consistent Warp simulations of NDCX-II, from source through "tilt" core, guide the design

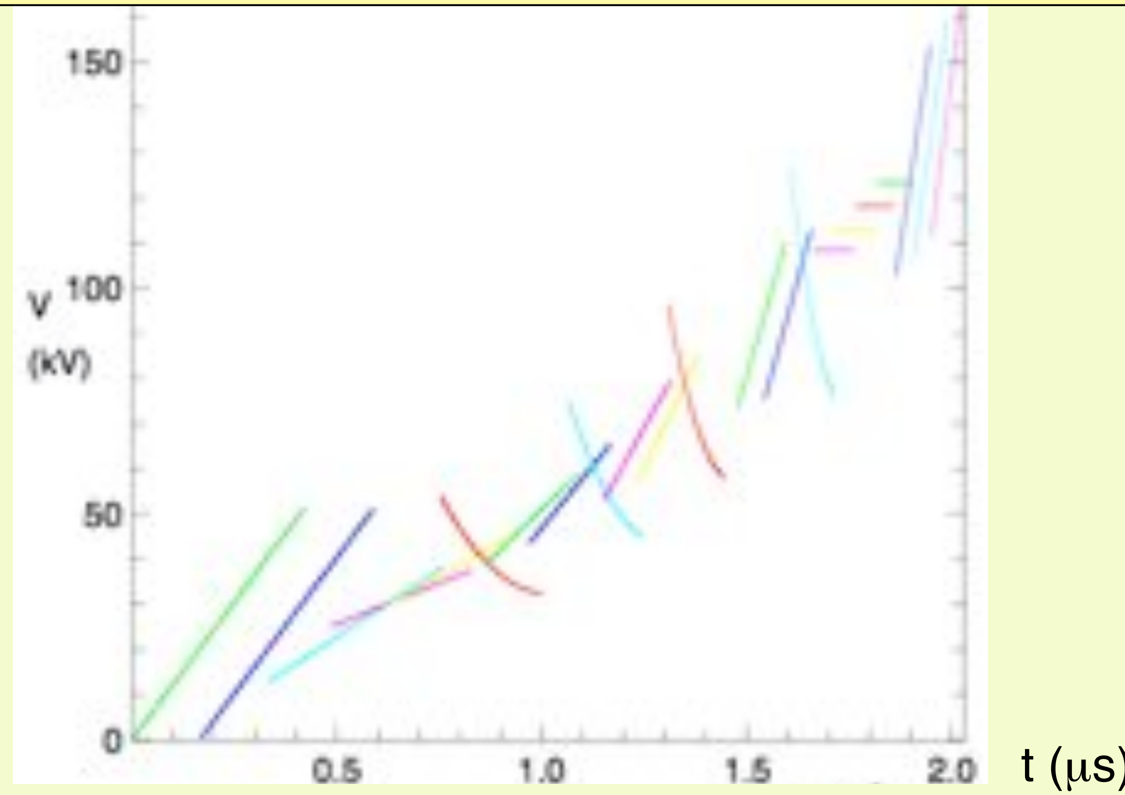


A simple 1-D beam model allows rapid scoping; goal is to use only accelerating waveforms that are readily generated



Time evolution of (z,v_z) phase space (moving window)

Waveforms — a collection of triangles, rising curves ~ 1-cos(t/τ), trapezoids, flat-tops, & decay curves — are the building blocks of longitudinal dynamics

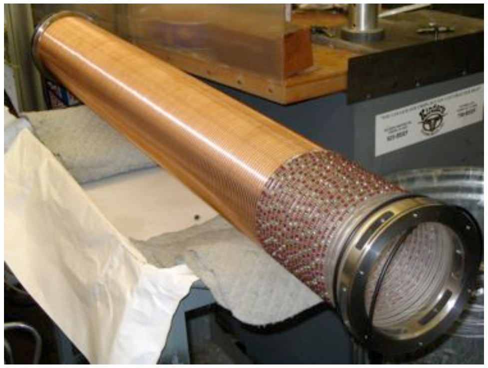


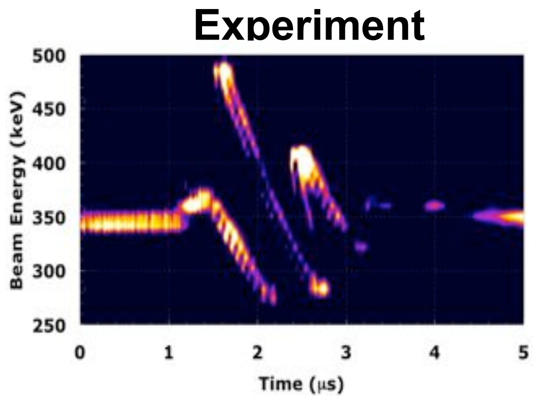
Pulse-Line Ion Accelerator (PLIA) may serve as a compact "afterburner" or an alternative front end

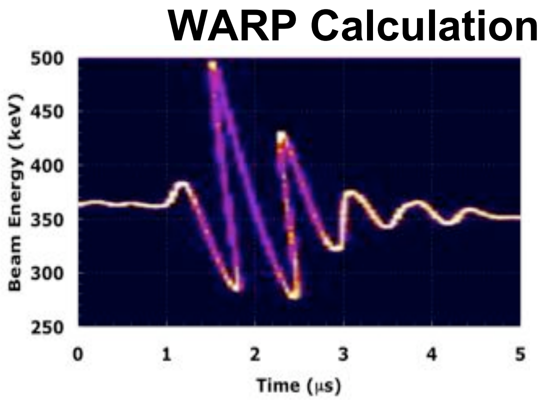
A traveling wave on a helical pulse line accelerates the ion bunch

- –"surfing" mode: acceleration of short bunch;
- –"snowplow" mode: aceleration and bunching of long pulse

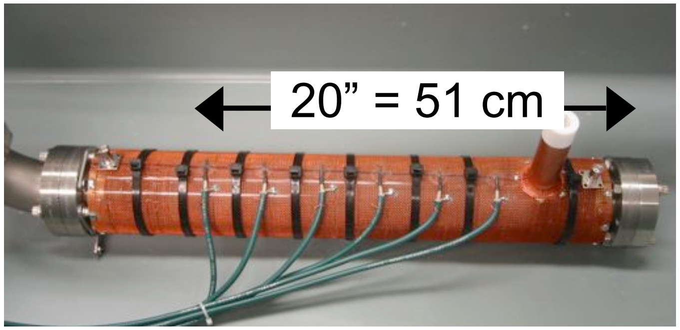
Proof-of-principle test on NDCX-I: acceleration & longitudinal bunching







Voltage gradient was limited to < 0.2 MV/m by partial discharges in the vacuum



Scaled helix for high gradient testing

- so far, peak gradient 0.35 MV/m
- partial discharges traced to high frequency ringing from spark gap pulser, now reduced; further reduction is being pursued

NDCX-II is on the path to heavy-ion-driven HEDP & fusion energy

- **NTX and NDCX-I have confirmed beam compression and focusing in plasma**
- **HIFS-VNL Warm Dense Matter experiments are beginning:**
  - **Metallic foam studies at GSI**
  - **Target heating experiments (~.2 - .5 eV) to begin soon on NDCX-I**
- **Physics & engineering studies supportive of NDCX-II are progressing:**

  See posters Tu PM (JP8): Welch 56, Sefkow 60, Startsev 62, Kaganovich 63, Henestroza 70

  Fri AM (YP8): Henestroza 25

- **Applications of NDCX-II are compelling:**

  (1) uniformly-heated 1 eV WDM physics

  (2) heavy-ion direct-drive target physics relevant to IFE
  - **ion ablative drive (w/ blow-off plasma)**
  - **hydro stability (w/ volumetric stopping): double-pulse experiments**

  See posters Tu AM (GP8): Veitzer 71, Bieniosek 72, Ni 73

  W AM (NP8): Barnard 48, Logan 49

Backup slides

A user facility for ion beam driven HEDP/WDM will have unique characteristics

Precise control of energy deposition

Large sample sizes compared to diagnostic resolution volumes (~ 1's to 10's μ thick by ~ 1 mm diameter)

Uniformity of energy deposition (<~ 5%)

Ability to heat all target materials (conductors and insulators, foams, powders, ...)

Pulse long enough to achieve local thermodynamic equilibrium

A benign environment for diagnostics

High shot rates (10/hour to 1/second)

Potential for multiple beamlines/target chambers

We have identified a series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1	NDCX-2
Metallic foam experiments at GSI	**0.25 - 0.5 eV**		
Measure target temperature using a beam compressed both radially and longitudinally	**Low**	√	
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	**Low**	√	
Positive - negative halogen ion plasma experiment	**>0.4 eV**	√	√
Two-phase liquid-vapor metal experiments	**0.5-1.0**	√	√
Critical point measurements	**>1.0**	**?**	√

time

NDCX-II paves the way for …

IB-HEDPX (with “CD0”)
5 - 15 year goal
20 - 40 MeV, 0.3 - 1.0 μC
WDM User facility

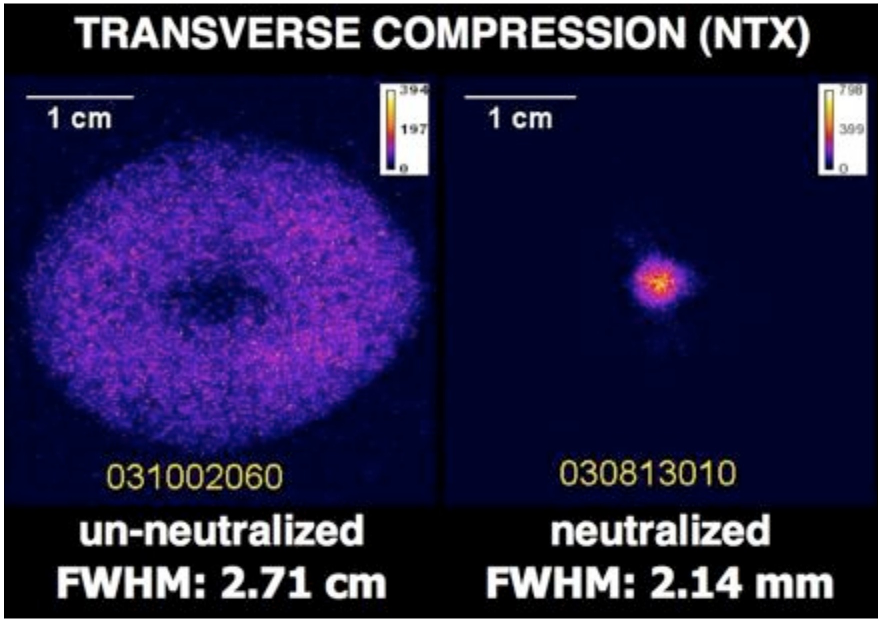
10 kJ Machine for HIF
10 - 20 year goal
Target implosion physics

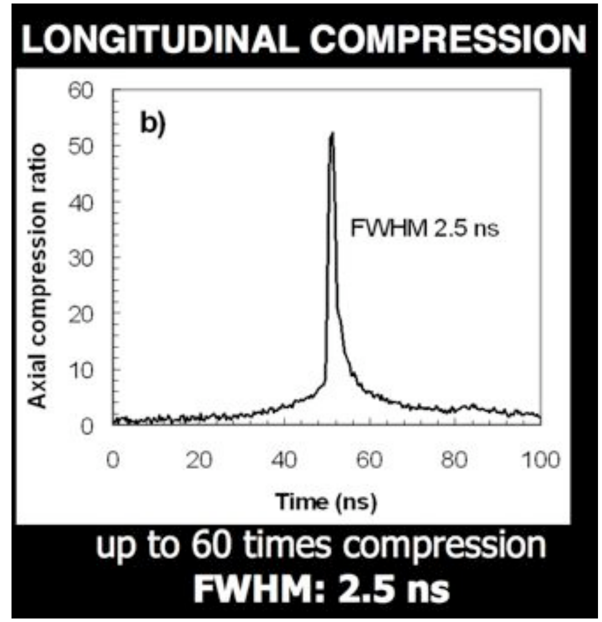
Currently there are two broad classes of “hydro experiments” that may be proposed for NDCX II

1. Ion energy coupling experiments
   - Outflowing material causes ion beams to penetrate less deeply over course of pulse
   - Can coupling be optimized via intensity and energy variations over space and time?
   - Simplest experiment: a double-pulse test
2. Stability experiments
   - Volumetric stopping affects growth of Rayleigh-Taylor instability differently than surface energy deposition.
   - Can we study this instability on NDCX II?
     - This worked well with Neon at 23 MeV
     - We are evaluating R -T experiments using Li

       (Li range in H is 10x higher than in Al, so lower temperature)

NDCX-I, and the earlier Neutralized Transport Experiment (NTX), showed that plasma can cancel a beam's space-charge repulsion





PRL 95, 234801 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Drift Compression of an Intense Neutralized Ion Beam

P. K. Roy,[1] S. S. Yu,[1] E. Henestroza,[1] A. Anders,[1] F. M. Bieniosek,[1] J. Coleman,[1] S. Eylon,[1] W. G. Greenway,[1] M. Leitner,[1] B. G. Logan,[1] W. L. Waldron,[1] D. R. Welch,[2] C. Thoma,[2] A. B. Sefkow,[3] E. P. Gilson,[3] P. C. Efthimion,[3] and R. C. Davidson[3]

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Longitudinal compression of a velocity-tailored, intense neutralized K^+ beam at 300 keV, 25 mA has been demonstrated. The compression takes place in a 1–2 m drift section filled with plasma to provide space-charge neutralization. An induction cell produces a head-to-tail velocity ramp that longitudinally

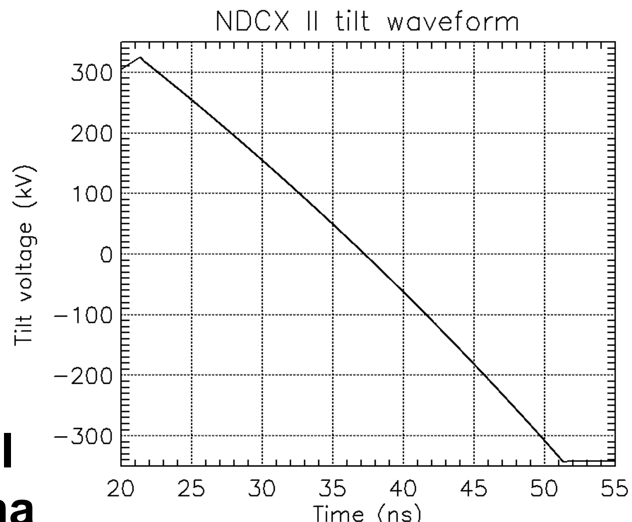
From Enrique Henestroza's earlier Warp runs

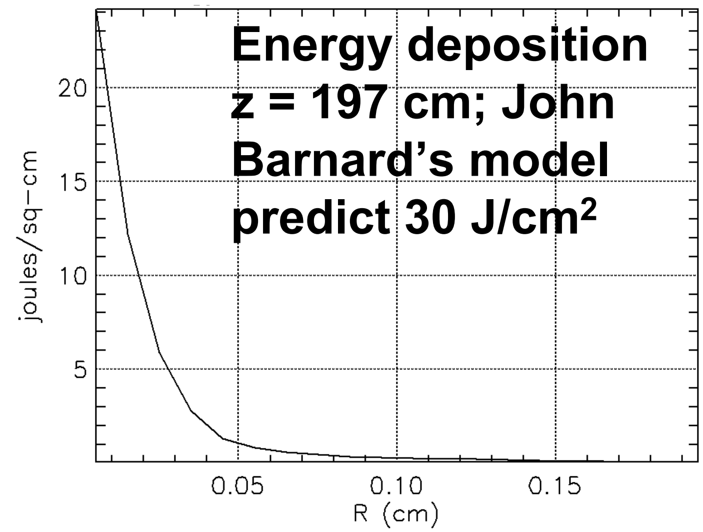
- Before drift compression ($z = 4.97$ m)
  - $v_z = 0.955 \times 10^7$ m/s $\beta = 0.032$
  - $\langle \delta v / v_{rms} \rangle = 2.4 \times 10^{-4}$, $kT_{||} = 2\, E \langle (\delta v_z / v_z)^2 \rangle = 0.32$ eV
  - $\varepsilon_n = 0.4$ mm-mrad
  - $I_{max} = 0.7$ A
  - $Q = 0.03$ μC
  - $\lambda_{max} = 0.073$ μC/m
  - $l_b = 0.57$ m
  - $\Delta t = 33$ ns (FWHM)

    = 60 ns (FWFM approximate parabolic pulse) -> 1 ns

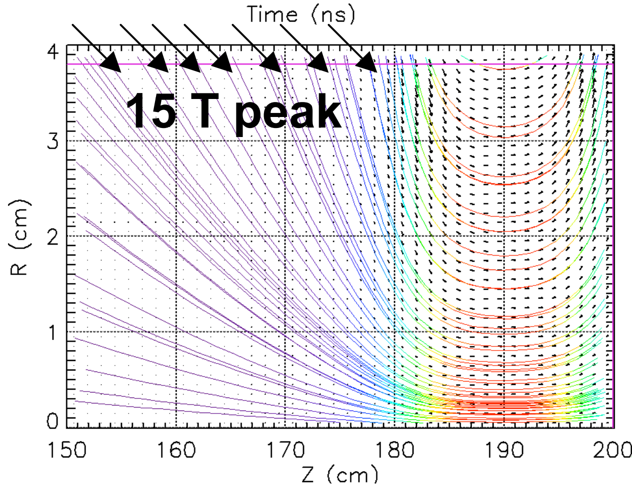
Tilt applied in a single gap

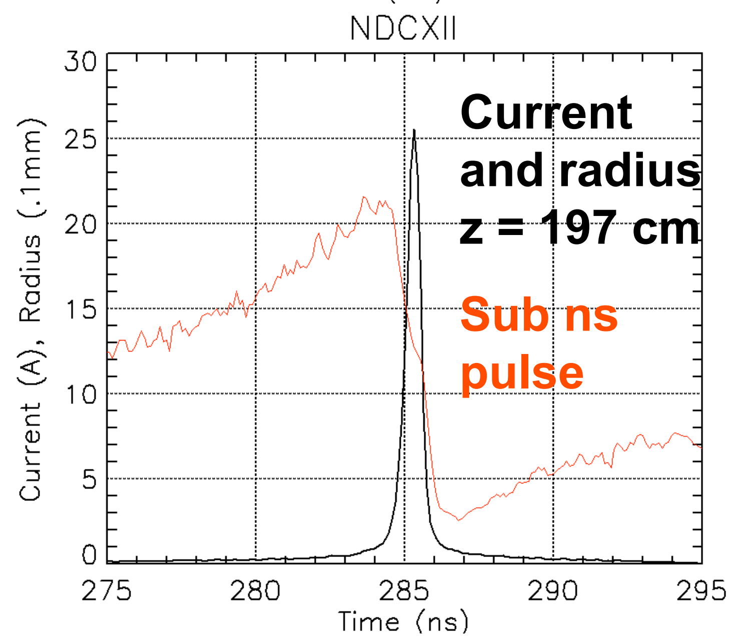
- 30 ns, 20% energy tilt; L = 220 cm ideal waveform
- design is likely for several ATA cells not single 650 MV gap





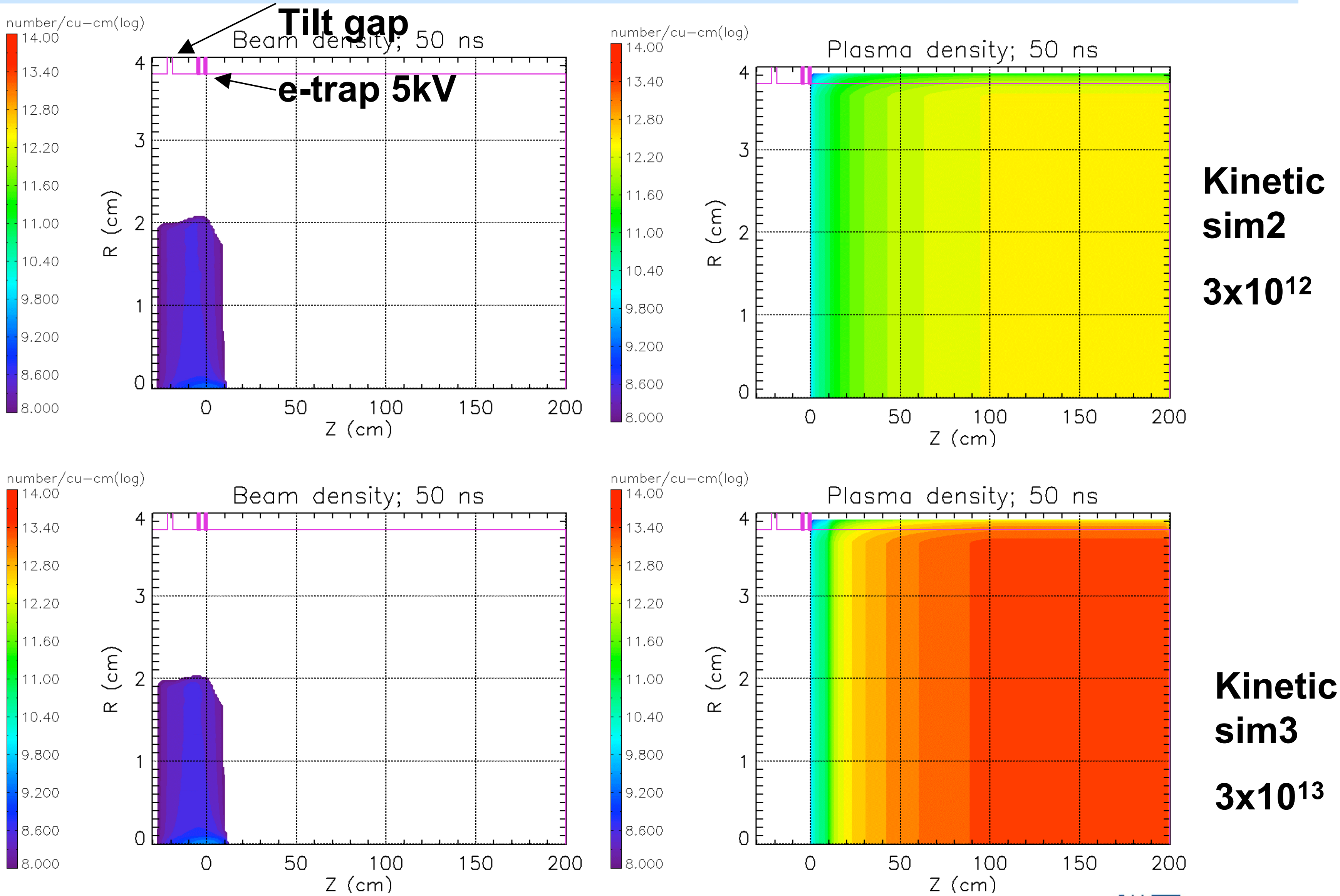
Radial plasma sources would help fill solenoid





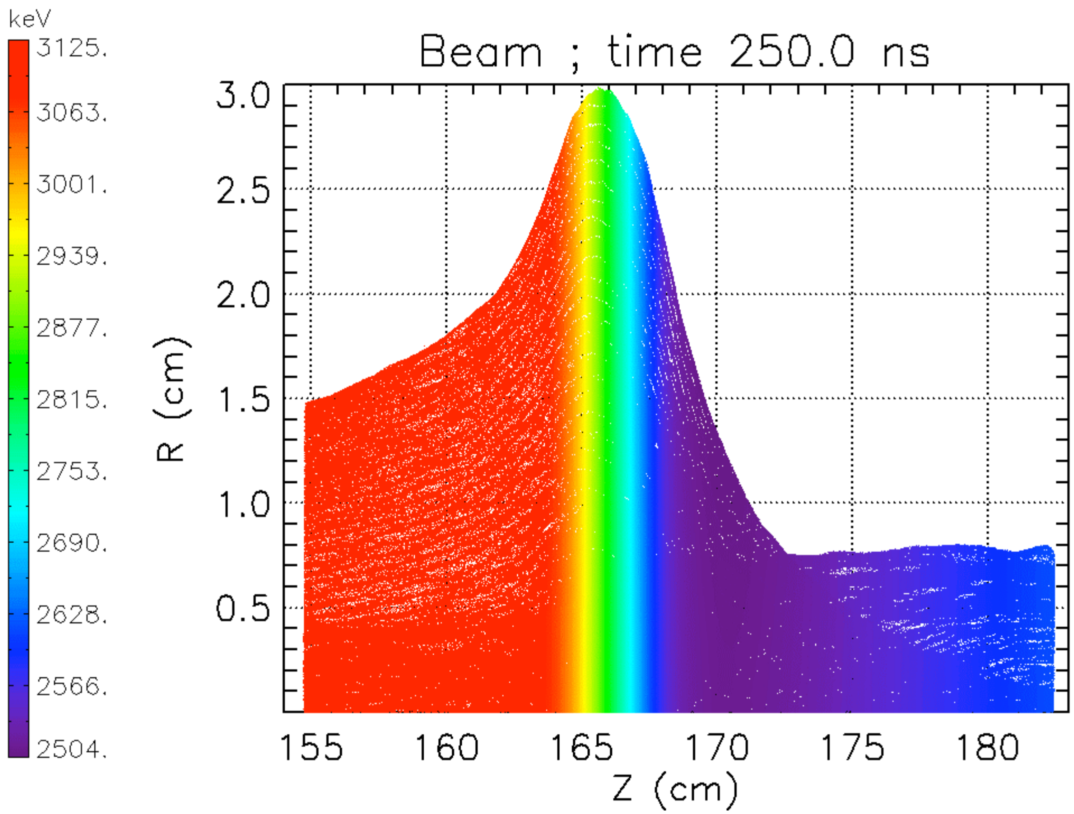
Ohm's Law results for $n_p = 10^{13}$ cm^{-3}

Assumed kinetic transport setup



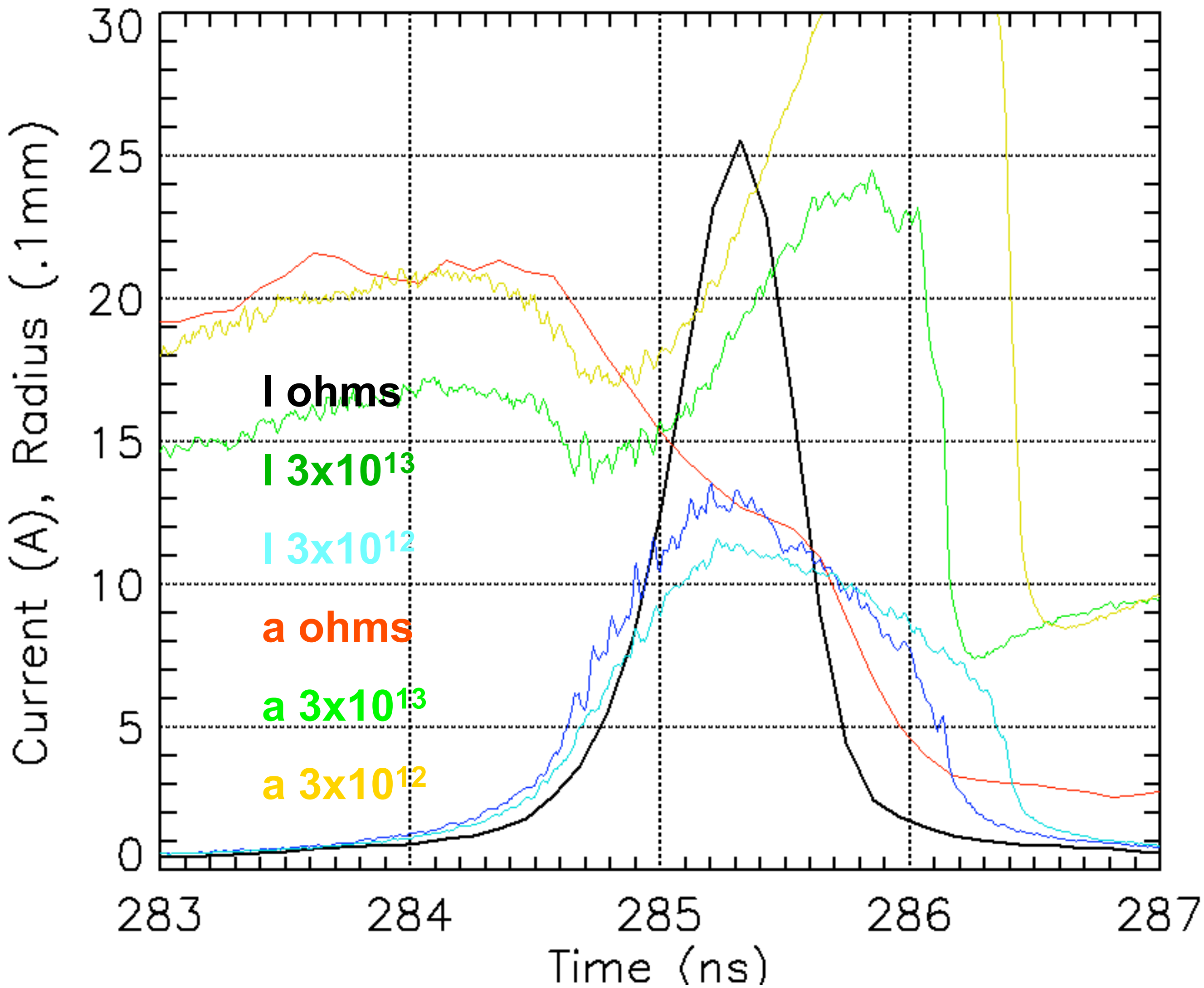
Applied tilt diverges compressing beam

- Time dependent tilt application will require -11 mrad compensation



Beam just upstream of FF solenoid

Beam conditions at target



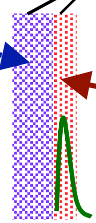
Axial focus a bit downstream in kinetic simulations – need slightly strong tilt voltage

Double-pulse planar target interaction experiments should reveal *unique* heavy-ion direct-drive coupling physics

Solid D_2 "payload"

Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

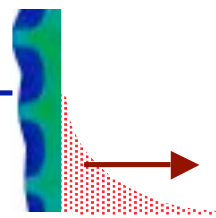
Time just before first pulse



Ablator D_2 layer ~ > than initial ion range

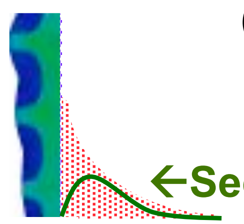
First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

2nd higher energy ion pulse arrives, and stops *partly within ablation blow-off* (in 1-D)

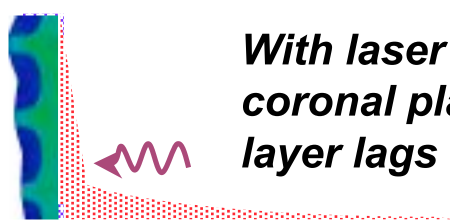


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses interacting with ablation layer mass?

←Second ns ion beam pulse dE/dx

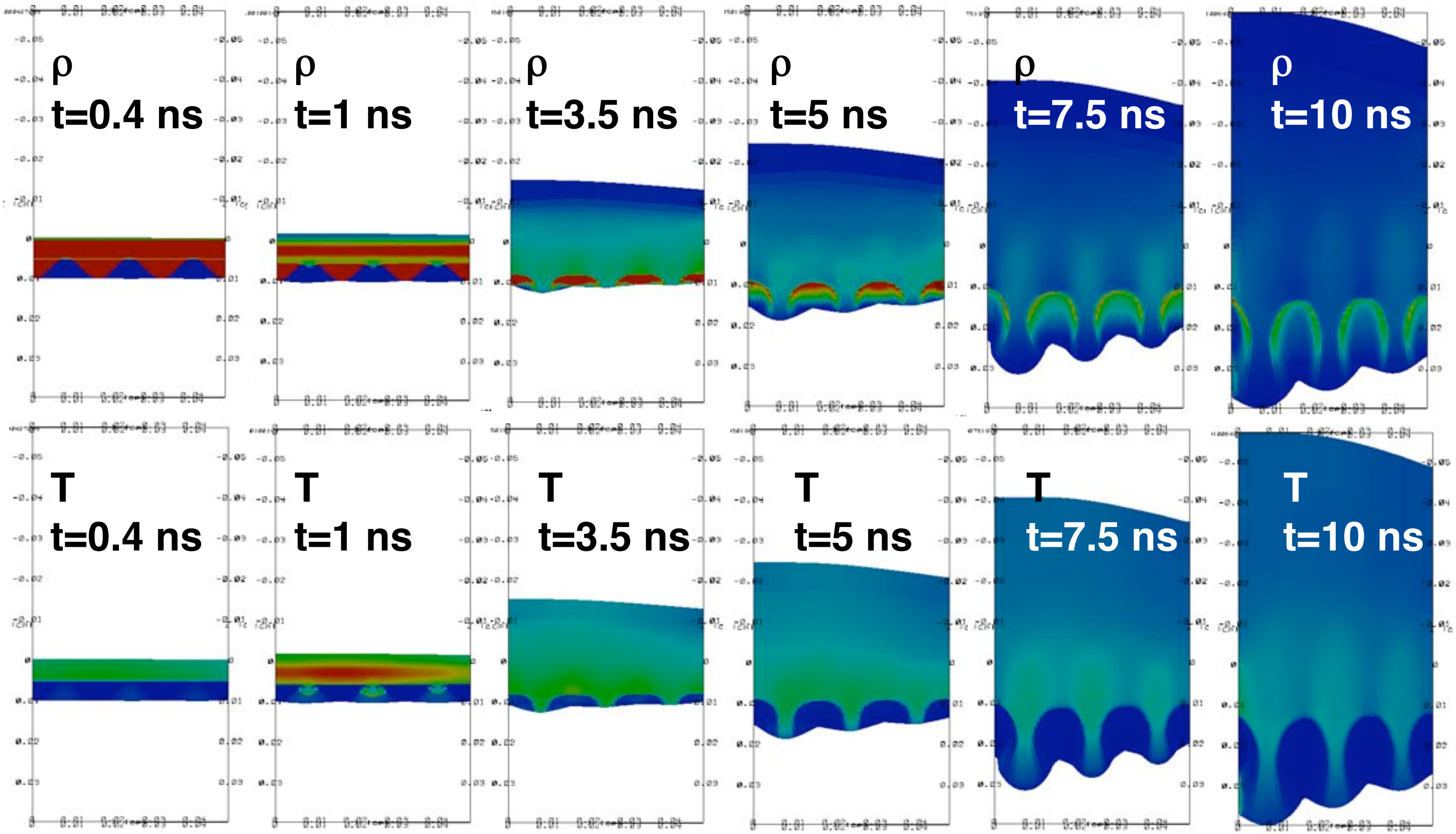
(2) How is RT growth affected (any "cloudy day" effect?)

With laser direct drive, later pulse ablates at fresh critical density layer further left



With laser direct drive, light transmits through most coronal plasma→ Absorption in inverse bremsstrahlung layer lags behind dense shell trajectory

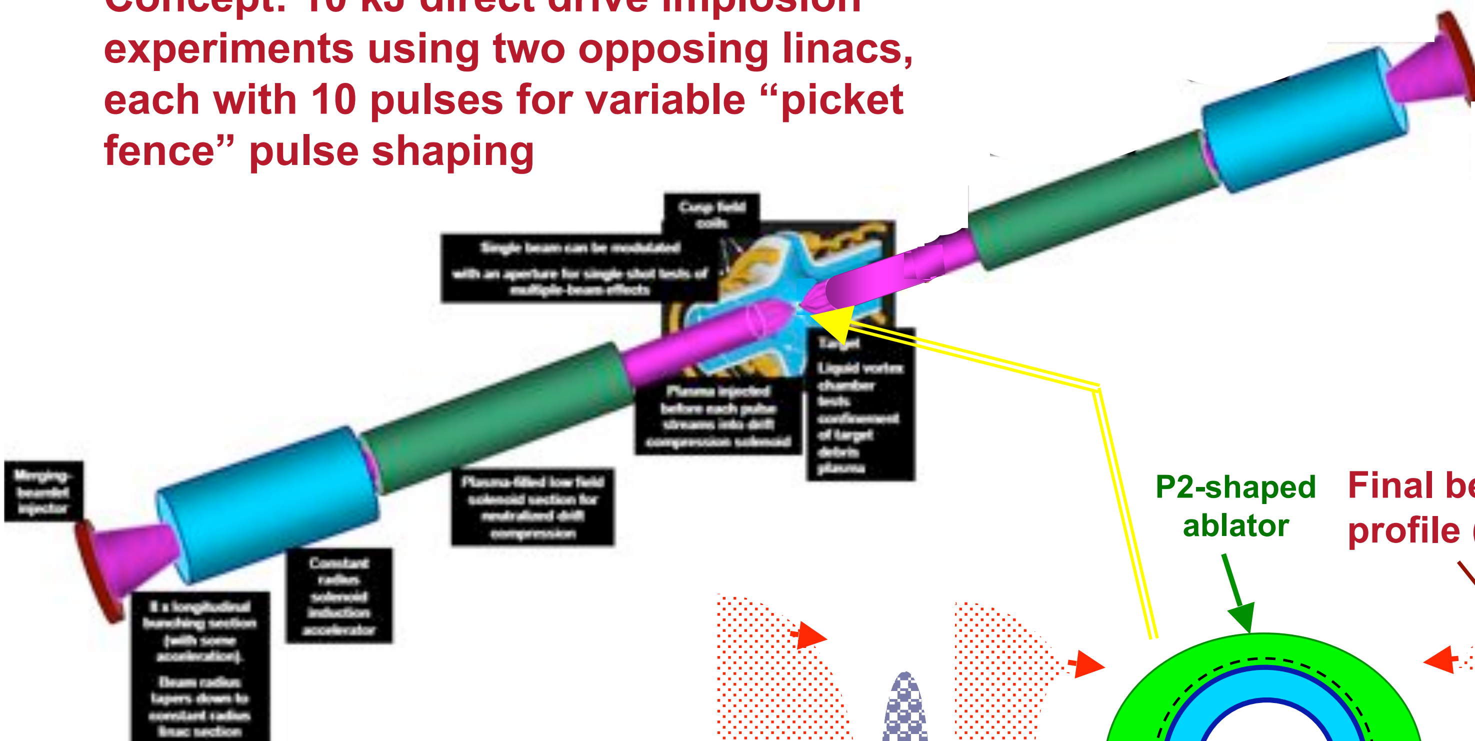
We have used the LLNL HYDRA code to show how unique heavy ion direct drive hydrodynamics as well as WDM can be studied on NDCX-II

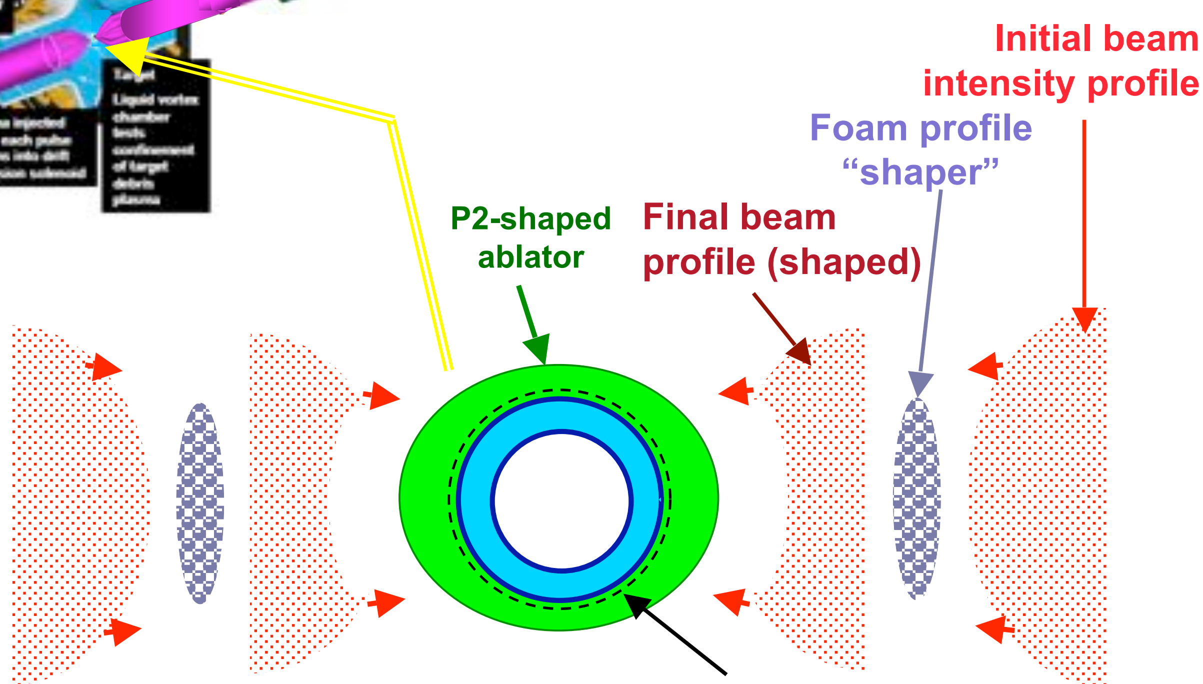


Can modulated beams stabilize ion Rayleigh-Taylor modes? (S. Kawata)

An IRE-scale new accelerator tool can explore polar direct drive hydro physics with heavy ions in parallel with NIF.

Concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable “picket fence” pulse shaping



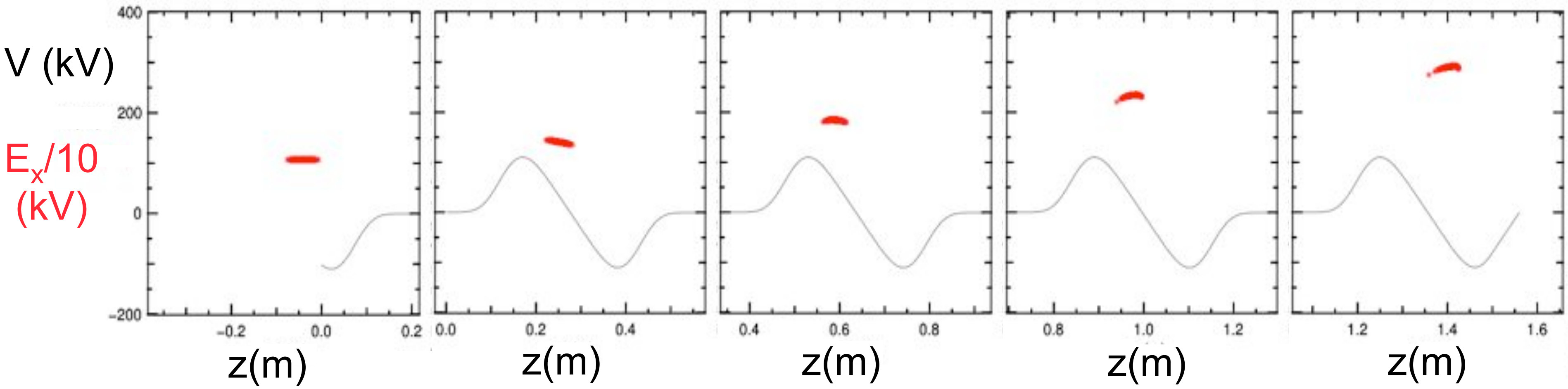


Three “knobs” to control P2 asymmetry with two beams:
1. Upstream GHz wobblers
2. Foam profile shapers
3. Ablator shaping

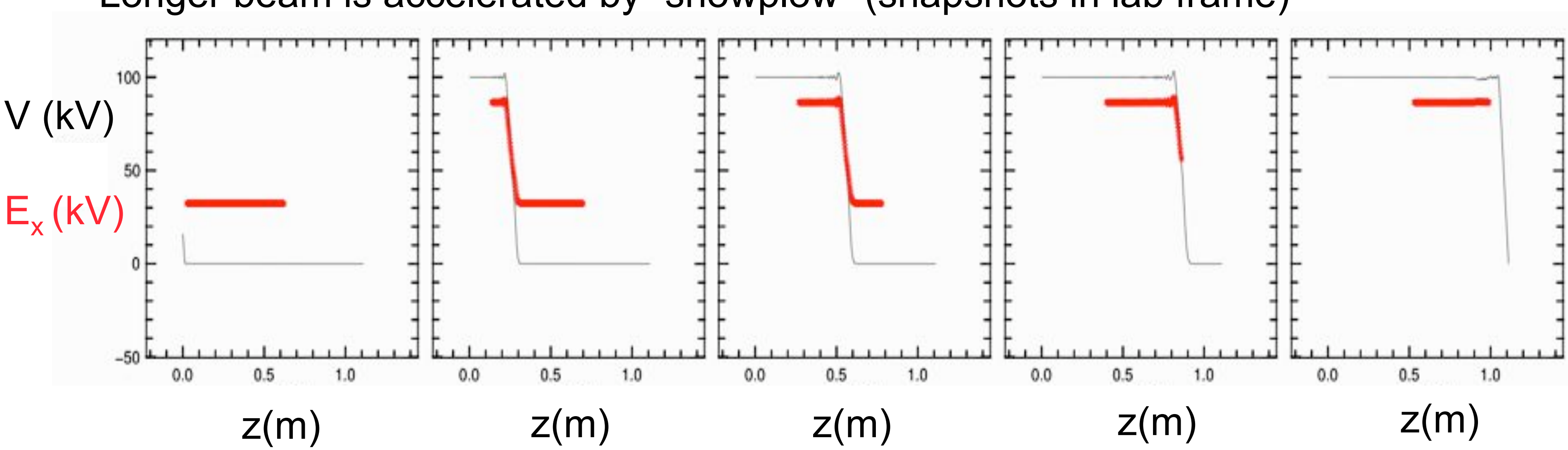
Goal is implosion drive pressure on the Cryo D_2 payload with < 1 % non-uniformity

PLIA can be operated in a short-pulse “surfing” mode or a longer-pulse “snowplow” mode

Short beam “surfs” on traveling voltage pulse (snapshots in wave frame)

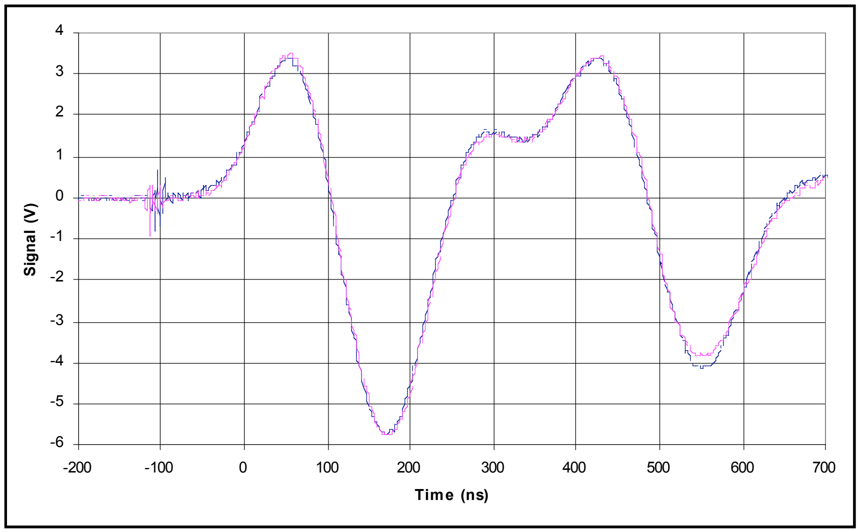


Longer beam is accelerated by “snowplow” (snapshots in lab frame)

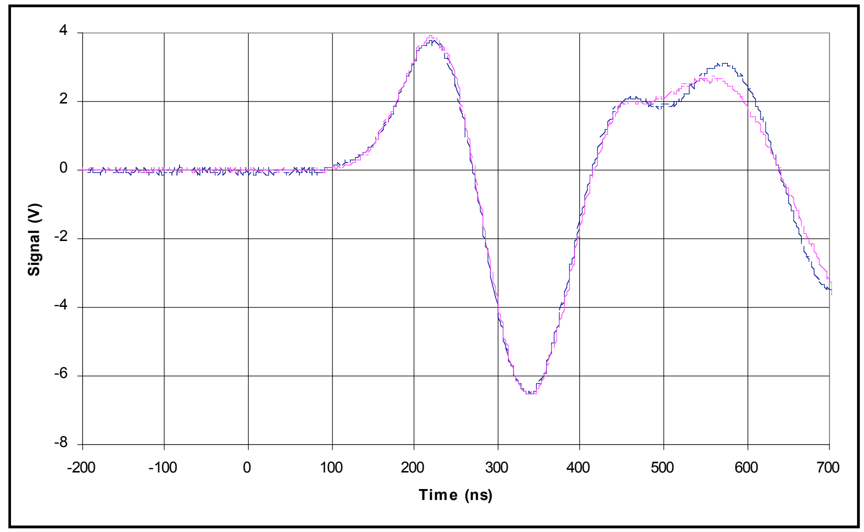


Scaled Helix voltage waveforms showing a peak gradient at the input of ~3.5 kV/cm with minimal loading when partial discharges occur

Input voltage (raw signal)



Output voltage (raw signal)



Blue traces are without a partial discharge.
Pink traces are with a partial discharge.